Thermally activated building systems in office buildings: impact of controller settings on energy performance and thermal comfort

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1. ABSTRACT

The control strategy and controller settings in a building with Thermally Activated Building Systems (TABS) are of major importance in achieving a good energy performance and thermal comfort. For a high quality office building in Belgium, the impact on energy use and thermal comfort of the settings of a feedback controller are investigated, in order to derive an optimal combination of controller settings and to provide scientifically sound recommendations to the commissioning process of this building. The location of the temperature sensor, heating and cooling water supply temperatures, heating and cooling set points, night time setback and ventilation air temperature control are the investigated controller settings. A low energy use and a low thermal discomfort are achieved by controller settings which take into account the thermal inertia of the TABS. Controlling the TABS surface temperature, using relatively low heating and high cooling temperatures and activating cooling at a lower temperature than the thermal comfort limit, are proven to result in a good balance between energy use and thermal comfort.

Keywords: Thermally Activated Building Systems (TABS), controller settings, office building simulation, energy performance, thermal comfort

2. INTRODUCTION

The control of Thermally Activated Building Systems (TABS) has been the subject of several scientific articles. The choice of control strategy and controller settings has been proven to play a decisive role in reaching both thermal comfort and low energy use.

Olesen et al. (2002) study the effect of pump operation time, intermittent pump control and supply water temperature on the energy use for a TABS office building in summer period. Night time operation is beneficial from the energy point of view, but with a slightly higher discomfort. Intermittent pump control can dramatically lower energy use, while maintaining a comparable level of comfort. For the supply temperature, a slightly inclined, outdoor temperature dependent curve appears to be the best in balancing energy use and thermal comfort.

Tödtli et al. (2009) define a combination of a compulsory outdoor temperature dependent heating and cooling curve, an optional room air temperature feedback and an optional intermittent pump control. The feedback module allows a correction on the calculated set points from the heating and cooling curve, while the intermittent pump control tries to benefit from the different heat transfer processes from water to concrete and from concrete to room air.

The forced convection heat transfer rate from water to tube wall is much higher than the conduction heat transfer rate. Therefore, after a reasonably short period of time, the tube wall reaches a temperature almost equal to the water temperature. Consequently, there is no longer heat transfer from water to tube. By shutting down the circulation pump, the heat or cold is allowed to diffuse into the concrete.

Sprecher et al. (2005) define one outdoor dependent supply temperature curve in combination with a pump operation time control. Moreover, they add the concrete core temperature as an extra corrective variable in their building controller. This temperature together with the room air temperature is used to correct the calculated supply temperature.

Sourbron et al. (2009) demonstrate that for room air temperature feedback control, changing the controller settings has a major impact on the resulting thermal comfort and energy use. Non adapted settings lead to inefficient use of energy, as observed in measurements as well as in simulation results.

The outdoor temperature dependency of the heating and cooling supply temperature appears to be relatively weak. Moreover, by applying this open loop control strategy, the controller can not compensate for the occurring heat gains or heat losses, nor will it fully grasp the dynamic effects of the TABS. The use of the return temperature as the controlled variable can provide information on the state of the TABS, but it needs water circulation through the TABS.

Furthermore, the impact of changing control settings on energy use and thermal comfort and the mutual influence of control settings are seldom investigated. It is the aim of this paper to derive conclusions regarding the robustness of controller performance towards controller settings. An on-off feedback controller is used, based on a continuously measurable variable, thus not dependent on pump operation. The results of this study are used to commission a new TABS office building in Leuven.

3. BUILDING SIMULATION

Since this simulation study aims at making a sensitivity analysis of energy use and thermal comfort on controller settings , it has been chosen to model one landscape office at the south façade with a used surface of 554 m² (indicated by the arrow on Figure 1) in the building system simulation program TRNSYS (SEL-University of Wisconsin et al. 2005). In the HVAC layout, this zone represents one controlled area with its own supply and return. Therefore, it works independently from the other building zones and can be treated as such. An occupation density of 1 pers/10 m² is assumed, which can be considered as relatively high for a landscape office (EN15251 (2007) prescribes 1 pers/15 m² for landscape offices). However, since the possibility exists that the office zone is subdivided into single office cells, this value was kept.

3.1 Building description

End 2004 Interleuven, a project development company in Vlaams-Brabant (Belgium), started the development of two buildings, ICT1 and ICT2. They are in use since spring 2006. ICT3 and ICT4 have an analogous volume structure as ICT1 and ICT2 and the whole project is part of a master plan to develop a science park near the K.U.Leuven. The aim of the science park is to house technology companies and spin-off's from the K.U.Leuven.

Where ICT1 and ICT2 are equipped with standard HVAC systems, the ICT3 and ICT4 buildings have a combination of techniques which makes them low energy and sustainable office buildings: high insulation levels combined with thermally activated floors, a ground source heat pump system and air preconditioning by a ground tube.

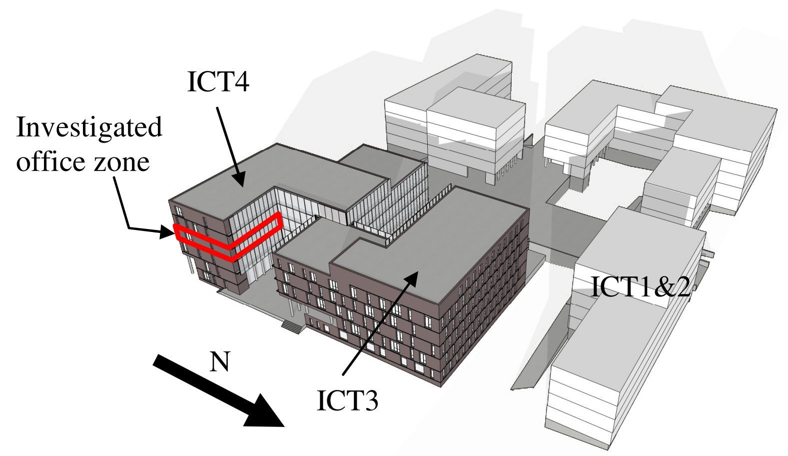

Figure 1 : ICT3 and ICT4 as part of Science park Arenberg (Leuven, Belgium) (Poponcini & Lootens, ir. architecten bvba)

The combination of the HVAC techniques and the possible comparison between ICT3 and ICT 4 on the one hand and ICT1 and ICT2 on the other hand make this twin building an ideal research subject for monitoring and evaluating the HVAC system.

Table 1: ICT3 and ICT4 building parameters

	ICT3	**ICT4**
Heated volume (m³)	12 842	13 451
Heated total surface (m²)	4475	4671
Heated surface office space (m²)	3385 (76%)	4266 (91%)
Heated surface restaurant (m²)	603	-
Insulation wall (PUR)	10 cm	
Insulation roof (PUR)	14 cm	
Window (U_{glass} ; g) (W/m².K ; -)	1.1 ; 0.61	
Glass façade (U_{glass} ; g) (W/m².K ; -)	1.1 ; 0.40	
Transmission area above ground (m²)	2558	2953
Transmission area windows (m²)	222	1050
Transmission area glass façade (m²)	334	475
Design power heating (T outside = -10°C) (kW)	302	305
Installed heating power (kW; W/m²)	760; 170	766; 164
Installed cooling power (kW; W/m²)	404; 90	487; 104
Calculated heating demand (MWh; kWh/m²)	372; 40	
Calculated cooling demand (MWh; kWh/m²)	862; 94	

The building specifications are listed in Table 1. Apart from the office space, ICT3 also has a restaurant/cafeteria and coffee bar with a large pavement on the ground floor, which will be used by the people of the two buildings.

The inner façades - towards the patios in between ICT3 and ICT4 - are fully glazed. At a distance of 80 cm a fixed sunscreen is provided which also gives some privacy to the people working in the offices. The orientation of the building is chosen such that in winter solar gains can be used to heat the building, but in summer a fixed sunscreen blocks excessive solar radiation, eliminating overheating by solar radiation. Fresh air is preconditioned by a system of ground tubes, which preheat the air during winter and precool the air during summer conditions. Besides this measure, the air handling units are equipped with high efficiency rotary heat recuperation wheels.

The floors of the building are thermally activated, which means that water tubes are incorporated inside the structure and heat up or cool down the structure to provide the necessary heat supply or removal. Heat is exchanged mostly through radiation, which creates a highly comfortable environment.

Using thermally activated building systems enables the use of relatively high water temperatures for cooling and relatively low water temperatures for heating. This creates a perfect condition for using heat pumps for heating and ground heat exchangers as a source for cooling.

The building layout is presented in Table 2. Levels +1, +2 and +3 are three identical office floors whereas the ground floor houses the entrance hall, restaurant and snack bar with pavement.

Table 2 : ICT3 and ICT4 building layout

Floor number	**Function**
+4	Technical level
+1, +2 and +3	Typical office level Landscape office, up to 6 smaller units
0	Entrance hall, restaurant, cafeteria and pavement
-2 and -1	Parking place (188 cars)

3.2 Heat gains

Heat gains are calculated using the following values :

- 75 W/pers sensible heat gain (42% convective - 58% radiative) (ASHRAE 2009).
- Appliances : 150 W/person (145 W/PC + 35 W/monitor (Duška et al. 2007), diversity factor 0.75, and 215 W/printer, 1 printer/8 pers, diversity factor 0.5); (30% convective - 70% radiative (ASHRAE 2009).
- Lights : 10 W/m² (50% convective - 50% radiative). Since 70% of the light armatures are daylight controlled, their energy consumption is reduced with 35%, according to Reinhart (2004).

3.3 Infiltration rates

Van Bronkhorst et al. (1995) use, for a building with a maximum of 5 stories, the approach to cut infiltration rates to 25% during system operation, compared to the 'fans off' situation. Furthermore, they use a 90% correction factor on the building volume for the presence of unoccupied spaces, furniture and walls.

Emmerich et al. (2005) present infiltration data for a large set of buildings, stating that 6% fulfils their target 'good practices' level of air tightness. Resulting infiltration air changes range from 0.02 h^{-1} to 0.05 h^{-1} in an overpressurized case (95% return air flow). In the current simulation the building is assumed to meet these criteria and an air leakage rate of 0.05 h^{-1} is used. During system shut down the infiltration rate is 0.2 h^{-1}. This is also in correspondence with the data of Emmerich et al. (2005). A 90% correction factor on the building volume is incorporated too.

3.4 Meteorological data and thermal comfort

The Typical Meteorological Year of Uccle (Belgium) is used as input to the building zone, as provided by the Meteonorm® weather database in TRNSYS. Thermal comfort is evaluated based on the standard criteria of ISO7730 Class B (ISO7730-2005), as presented in Table 3:

Table 3: Optimal operative temperature and operative temperature band for thermal comfort in office environment, according to Class B defined by ISO7730

Category	$T_{op,winter}$ (°C)	$T_{op,zomer}$ (°C)
B	22,0 ± 2,0°C	24,5 ± 1,5°C

This temperature band defines $T_{comfort,min}$ and $T_{comfort,max}$ during the year. The ISO7730 standard gives information about comfort temperatures in the heating season and in the cooling season, without specifying when these seasons start or end, or how the comfort temperature is related to the outdoor temperature. In this work the EN15251 (2007) approach is applied:

- Heating season: Outdoor running mean temperature $T_{rm} < 10$°C;
- Cooling season: Outdoor running mean temperature $T_{rm} > 15$°C;
- Linear interpolation is applied for temperatures in between those limits;

with T_{rm} the running mean outdoor temperature as defined by EN15251.

3.5 HVAC system layout

The HVAC system as simulated in the TRNSYS model consist of four major parts. The building zone has a TABS ceiling and TABS floor. Together with the air inlet and exhaust from the Air Handling Unit (AHU), those parts make up the emitting side of the HVAC system.

The AHU consists of an heat recovery cross flow heat exchanger, a heating coil and a cooling coil, characterized by the following parameters :

- 100% supply air flow: 36 m³/h per person (= 1980 m³/h)
- 95% return air flow

- 60% heat recovery efficiency
- Constant 18°C supply air temperature set point from 7 AM to 7 PM as basic control strategy

Humidity control was not integrated in the AHU. Simulation results confirm this design decision showing very little hours with too high or too low relative humidity. This is evidently caused by the mild Belgian climate for which the simulations were performed. The AHU supply air temperature will be one of the variables to be analyzed in the sensitivity analysis. The ground tube is not incorporated in the simulation model.

The TABS supply collector has two circuits supplying water (at the same temperature) to the ceiling and floor TABS. A pump is circulating the water, either to the boiler or to the chiller. The instantaneous controller settings determine the position of the three way valve in this circuit.

The first part of the simulation study (Section 4.1) determines the reference situation with an ideal emitting system and an ideal boiler and chiller of unlimited power.

In the second part (section 4.2 – Section 4.6) TABS are used and the heat and cold are produced by an ideal boiler and chiller with a limited power. Initially, this power is determined by the static heating and cooling load calculations: based on the results of the engineering study, these were both set to 33 kW (60 W/m²) for the simulated office zone. This value is corrected to 40 W/m² based on the results of the reference case.

The heating and cooling energy delivered to the AHU is assumed to be supplied by an additional boiler-chiller system, as it is the case in the real ICT-buildings.

3.6 Simulation parameters

The simulation is performed for a whole year. To obtain sufficient numerical stability of the controller, the time step is set to 0.1 h. The TRNSYS built in successive solver is used to solve the system equations.

3.7 Evaluation of the simulation results

Two performance indicators, one for energy use and one for thermal comfort, are used to analyse the simulation results:

$$\textit{Energy use index, case i}\left(EUI\right)=\frac{Q_{h,i}W_h+Q_{c,i}W_c}{Q_{h,net}W_h+Q_{c,net}W_c} \tag{1}$$

$$\textit{Thermal discomfort index, case i}\left(DI\right)=\frac{BL_iW_u+AL_iW_o}{BL_{net}W_u+AL_{net}W_o} \tag{2}$$

With: $Q_{h,i}$ [kWh/m²a] and $Q_{c,i}$ [kWh/m²a] the yearly heating and cooling energy use for simulation case i; BL_i [Kh] and AL_i [Kh] the number of Kelvin-hours respectively below the limit of $T_{comfort,min}$, and above the limit of $T_{comfort,max}$ for case i; the index 'net' refers to the energy use and Kh of the ideal heating and cooling case; W are the weights attributed to the different performance parameters. In this simulation study, the weights are equal, indicating that heating and cooling, and BL and AL are of equal importance.

Together with these two primary performance indicators, the ratio of heating to cooling energy provides information on the switching behaviour between heating and cooling of the concrete slab. Since the office building has generally more heat gains than heat losses, even in winter situation, from an energy balance point of view, more cooling than heating is required to maintain thermal comfort. A deviation from the standard ratio, provided by the ideal heating and cooling simulation, indicates a bad controller performance (Sourbron et al. 2009). The ratio can be made for the zone energy, the ventilation energy or the total energy, being the sum of zone and ventilation energy.

$$\begin{aligned} ratio_{zone,i} &= \frac{Q_{h,i}}{Q_{c,i}} \\ ratio_{vent,i} &= \frac{Q_{h,vent,i}}{Q_{c,vent,i}} \\ ratio_{tot,i} &= \frac{Q_{h,tot,i}}{Q_{c,tot,i}} \end{aligned} \tag{3}$$

3.8 Controller parameter selection

In the current simulation study, a feedback control strategy for the TABS system is analysed. The following terminology is used :

- The **sensor** measures a temperature (= controlled variable) and transmits this value to the controller.
- The **controller** compares this value to the set point and generates a corrective action to the controlled devices. In this case an on-off controller is used : the supply water flow starts when the set point is trespassed.
- The **controlled devices** are the TABS ceiling and floor.
- The **control agent** is the heating and cooling water supplied to the TABS, of which the supply temperature ($T_{h,s}$ and $T_{c,s}$) can vary.
- The **set point** is the desired value of the controlled variable (temperature in this case). There is a set point for heating and one for cooling : $T_{h,set}$ and $T_{c,set}$.
- The **controlled temperature** is the variable being controlled.

The controller parameters used in the current simulation study are listed in Table 4.

Table 4 : Overview of controller settings

	Controller settings
$T_{controlled}$	T_{ia} (indoor air), T_{op} (operative), $T_{TABS,core}$ (concrete core), $T_{TABS,surf}$ (concrete surface)
$T_{h,s} – T_{c,s}$	25-21; 28-18; 31-15
$T_{h,set}$	$T_{comfort,min}$; $T_{comfort,min}$ + 1; $T_{comfort,min}$ + 1.25;
$T_{c,set}$	$T_{comfort,max}$; $T_{comfort,max}$ - 1; $T_{comfort,max}$ - 1.25; $T_{comfort,max}$ - 2

The controlled temperatures are all continuously measurable variables in the control system, i.e. even with a non operating circulation pump, they can provide data to the building controller. The drawback of these controlled temperatures is the position dependency of their reading: installation of the sensors has to be carefully accomplished so that their reading gives a representative value. Other controlled temperatures like supply or return temperature do not have the feature of being independent of pump operation, hence a pump time control has to be combined (not considered in the current study). However they do not have the drawback of being position dependent.

Additional to these parameters and the corresponding settings, the following parameters are incorporated and evaluated in the analysis :

- Night setback: ($T_{h,set}$ -5) and ($T_{c,set}$ + 5) from 21 PM until 6 AM
- Ventilation air temperature control: $T_{vent,s}$ = 22°C from 7 AM to 8 AM (instead of 18°C) to decrease the possible temperature drop at the start of the working day

HVAC and ventilation schedule are fixed: from 6 AM – 9 PM and from 7 AM to 7 PM respectively.

4. SIMULATION RESULTS AND DISCUSSION

This section presents the results of the different simulation cases. After the ideal heating and cooling case, four TABS controller cases represent a step by step approach towards an optimal combination of the selected controller parameters and settings for the investigated office zone.

4.1 Reference case: ideal heating and cooling

As a reference case, the office zone is simulated with an ideal, 100% convective heating and cooling emission system with unlimited power, as provided by the TRNBUILD building model generator (SEL-University of Wisconsin-USA et al. 2005). In this way, the heating and cooling energy flows are directly coupled to the zone air temperature node of the model. If the zone air temperature T_{ia} at the end of the time step is within the heating and cooling set points, the zone is free floating. In the other case, when heating or cooling is necessary, the exact amount of power is supplied in order to make $T_{ia,t} = T_{set,t}$ at the end of time step *t*. The controller settings are listed in Table 5.

Table 5 : Controller settings for the ideal heating/cooling case

	Controller settings
$T_{controlled}$	T_{op}
$T_{h,s} - T_{c,s}$	Not applicable
$T_{h,set}$; $T_{c,set}$	$T_{comfort,min}$; $T_{comfort,max}$
Night setback	Yes
$T_{vent,s}$	18°C constant

This procedure poses a problem in evaluating thermal comfort of the zone, which is based on the operative temperature T_{op} of the zone. Since the ideal heating and cooling is controlled by the air temperature T_{ia}, this temperature is kept within the temperature set points $T_{set,h}$ and $T_{set,c}$. T_{op} will deviate from T_{ia} in the sense that it will be lower in the heating regime and higher in the cooling regime. With $T_{set,h} = T_{comfort,min}$ and $T_{set,c} = T_{comfort,max}$, thermal comfort evaluation based on T_{op} will therefore show considerable deviation from the expected ideal situation. Since the TRNBUILD building model cannot be modified, the approach, described in Table 6, is followed: a corrected T_{set} is calculated based on the definition of the operative temperature.

$$T_{op} = \frac{\left(T_{ia} + T_{surf,mean}\right)}{2} \tag{4}$$

With $T_{surf,mean}$ the area weighted mean surface temperature of the office zone.

Table 6 : Simulation model settings for ideal heating and cooling

	Standard settings	**Corrected settings**
Thermal comfort evaluation	$T_{comfort,\min} < T_{op} < T_{comfort,\max}$	$T_{comfort,\min} < T_{op} < T_{comfort,\max}$
Heating on	$T_{ia} < T_{set,h} = T_{comfort,\min}$	$T_{ia} < T_{set,h} = 2T_{comfort,\min} - T_{surf,mean}$
Cooling on	$T_{set,c} = T_{comfort,\max} < T_{ia}$	$T_{set,c} = 2T_{comfort,\max} - T_{surf,mean} < T_{ia}$

This measure enables the use of the default ideal heating and cooling of TRNBUILD while allowing thermal comfort evaluation based on T_{op}.

The results of the ideal heating and cooling simulation provides the data to determine the denominator of the *energy use index* and the *thermal discomfort index*:

$$Q_{h,net}W_h + Q_{c,net}W_c = 28 \, {}^{kWh}\!/_{m^2} \tag{5}$$

$$BL_{net}W_u + AL_{net}W_o = 9.64 \; Kh \tag{6}$$

The procedure used to correct the model settings for the default ideal heating and cooling, as presented in Table 6, results in a small thermal discomfort (eq. 6), whereas a zero discomfort is expected. This deviation is caused by the numerical discretisation and is therefore time step dependent, since $T_{h,set}$ of time step i (Table 6) is calculated with the $T_{surf,mean}$ value of time step (i - 1). Nevertheless, this value will be used as a reference for the thermal comfort evaluation of the other simulated cases.

Evaluating the zone ratio indicates that only for a few days of the year, there is a heating and cooling demand during one single day. For the majority of the days, either a heating or a cooling demand exists.

An other conclusion to be drawn from the ideal heating and cooling simulation, is that the heating and cooling power determined by the load calculations are 150% of the maximum heating and cooling power resulting from the dynamic simulation run. Disregarding the correct building dynamics and overestimating the heat loads in the load calculations cause this difference. The simulation results confirm that the assumption that heating and cooling power are almost equal : $Q_{h,max}$ = 35 W/m² and $Q_{c,max}$ = 38 W/m². The dynamic results are rounded to 40 W/m² and used as boiler and chiller power in the other simulation cases (instead of 60 W/m² based on the results of the engineering studies).

Due to the heat recovery in the AHU, the heating energy for the ventilation air is almost equal to the ventilation cooling energy (Table 7). Changing AHU control parameters, such as a daily startup sequence with elevated air temperatures to prevent undercooling of the building, will slightly change these values, but the order of magnitude remains the same. Omitting the heat recovery, changes the required heating and cooling energy dramatically: heating demand increases with more than 500%, while cooling demand decreases.

Table 7 : Heating and cooling energy of the ventilation air

Case	$Q_{h,vent}$ (kWh/m²)	$Q_{c,vent}$ (kWh/m²)	$ratio_{vent}$ (%)	$ratio_{tot}$ (%)
Heat recovery 60%	5.5	5.9	93	26
No heat recovery	29.6	2.1	1426	118

The former conclusion will have an impact when analysing the ground heat pump-direct cooling (HP-DC) system. If the ventilation energy could be supplied by the HP-DC system, this would be beneficial for the thermal balance of the ground. Without heat recovery, the total balance approaches unity closer than with heat recovery. Of course this benefit should be held against the increase of total energy required (+50%). In the case of heat recovery (with 60% efficiency) the total ratio is 0.26, meaning that the annual heating energy is much lower than the cooling energy, indicating a possible serious unbalance of the ground system.

The results of Table 7, showing an increase in cooling demand for the case with heat recovery, indicate that an intelligent control of the recovery system and its bypass is recommended to prevent heat recovery from overheating the ventilation air. Not being the scope of this article, this topic is omitted for the remainder of the simulation runs.

4.2 TABS Case 1: Sensitivity to $T_{controlled}$ and supply temperatures $T_{h,s}$ and $T_{c,s}$

In a first analysis, the sensitivity of the controller performance to the five controlled temperatures and the three supply water combinations of Table 4 is examined. Table 8 presents the controllers settings used in this case.

Table 8: Controller settings of TABS Case 1

	Controller settings
$T_{controlled}$	T_{ia} (indoor air), T_{op} (operative), $T_{TABS,core}$ (concrete core), $T_{TABS,surf}$ (concrete surface)
$T_{h,s} - T_{c,s}$	25-21; 28-18; 31-15
$T_{h,set}$; $T_{c,set}$	$T_{comfort,min}$; $T_{comfort,max}$
Night setback	No
$T_{vent,s}$	18°C constant

Figure 2 shows that the results are widely divergent. The marker with index (1,1) is the ideal heating and cooling result. All other results are presented relative to this reference case, as defined by Equations (1) and (2).

T_{ia} results in a low discomfort, but a high energy use. Due to the thermal inertia of the concrete floor, the TABS are always reacting too slowly to controller signals. This also causes a frequent switching between heating and cooling during a single day, characterized by a yearly $ratio_{zone}$ of 54%, while $ratio_{zone,reference}$ is only 10% . This corresponds to the results of Sourbron et al. (2009).

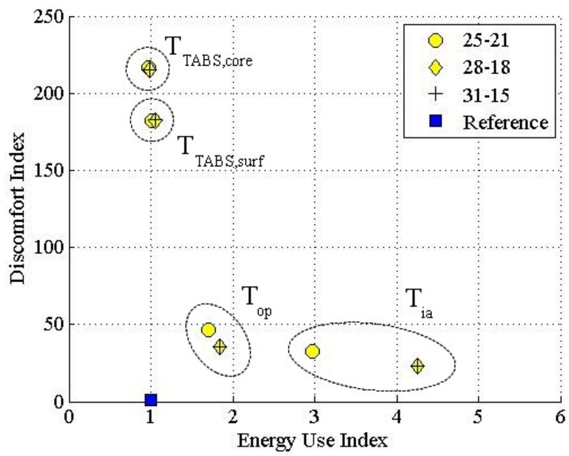

Figure 2: Sensitivity of controller performance to $T_{controlled}$ and supply temperatures $T_{h,s}$ - $T_{c,s}$

The results for T_{op} show a major improvement concerning the *EUI*. The daily switching behaviour between heating and cooling is decreased substantially, resulting in a $ratio_{zone}$ of 31%. The *DI* shows a minor increase in discomfort compared to the T_{ia} case.

With $T_{TABS,surf}$ or $T_{TABS,core}$ as the controlled temperature, the discomfort rises dramatically. Both result in an energy use comparable to the ideal heating and cooling case, but are not able to maintain comfort in the office zone. Again, the high thermal inertia of the TABS causes the heating or cooling, being switched on at $T_{comfort}$, to react too late.

The temperature supply setting '25-21' is capable of reducing the energy use in the T_{ia} and T_{op} setting, but with a higher discomfort as a consequence (+50% for T_{ia} and +30% for T_{op} compared to the '28-18' setting). The $ratio_{zone}$ reduction of 11% for T_{ia} and 1% for T_{op} explain the *EUI* reduction. For $T_{TABS,surf}$ and $T_{TABS,core}$ the results are independent of the supply temperatures. The results for the '28-18' and the '31-15' settings are hardly different for all controlled temperatures. Their intermediate results show a very small shift from Q_h to Q_c and from AL to BL if $T_{h,s} – T_{c,s}$ is changed from '28-18' to '31-15', but the overall *EUI* and *DI* remain equal. Therefore, the '31-15' setting is omitted from the remaining simulation cases. This conclusion is beneficial for the HP-DC system, who's performance increases with lower heating and higher cooling temperatures.

4.3 TABS Case 2: The effect of night setback and $T_{vent,s}$ on the controller performance

Applying night setback has a positive effect on the energy use for the T_{ia} setting and hardly no effect for the controller settings where $T_{TABS,core}$ is used as the controlled temperature. The *DI* slightly decreases for T_{ia}, and slightly increases for $T_{TABS,core}$. The behaviour of T_{op} and $T_{TABS,surf}$ lies in between these two extremes. Since the overall effect of night setback is positive to neutral, this setting will be used for the remainder of the simulated cases.

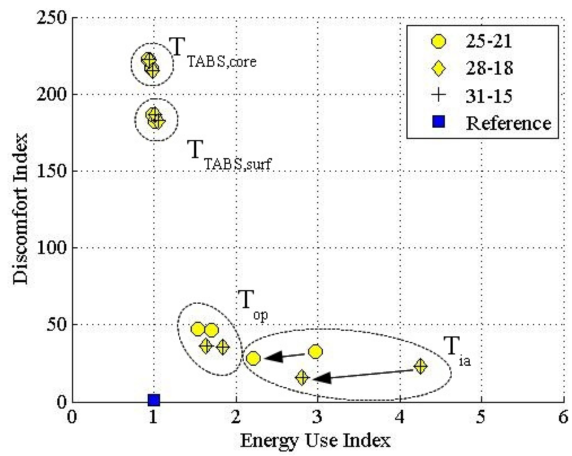

Figure 3 : The effect of night setback on the controller performance

The previous simulation cases show a number of hours with an operative temperature below the comfort limits. These hours are mostly situated at the beginning of the working day. Advancing the start time of the TABS operation reduces the BL-value but increases the AL-value by an almost equal amount. The resulting overall thermal comfort decreases and the energy use, both for heating and cooling increases. As an alternative, raising the ventilation air supply temperature during the first hour of AHU operation (from 7 AM until 8 AM) to 22°C, could improve this situation. The simulation results show an improved *DI* for all controlled temperatures. For the T_{ia} setting there is even a decrease in the *EUI*, caused by a lower zone heating and cooling demand. Again, this ventilation setting will be selected for the remainder of the simulated cases.

4.4 TABS Case 3: Heating and cooling set points

Decreasing the temperature band of the heating and cooling set points as indicated in Table 9, is expected to have a positive impact on the *DI*. Since the high thermal inertia of the TABS cause a delayed reaction on the control signals, heating and cooling should be switched on before these controlled temperatures reach the comfort limits.

Table 9 : Controller settings for TABS Case 3

	Controller settings
$T_{controlled}$	T_{ia}, T_{op}, $T_{TABS,core}$, $T_{TABS,surf}$
$T_{h,s} – T_{c,s}$	25-21
$T_{h,set}$- $T_{c,set}$	$T_{comfort,min}$- $T_{comfort,max}$; ($T_{comfort,min}$ + 1)-($T_{comfort,max}$ - 1); ($T_{comfort,min}$ + 1.25)-($T_{comfort,max}$ - 1.25)
Night setback	Yes
$T_{vent,s}$	22°C between 7 AM and 8 AM

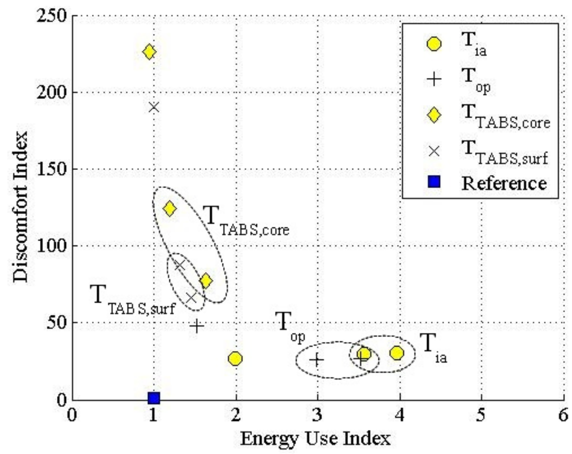

Figure 4: Influence of heating and cooling set points $T_{h,set}$ and $T_{c,set}$ (the adjusted settings are encircled)

These controller settings have a different influence on the results for the different controlled temperatures. With T_{ia} as the controlled temperature, the *EUI* increases significantly, while also the *DI* increases. The *DI* increase is caused by a rise of AL_{ia}, while BL_{ia} slightly decreases (BL_{ia} was already small) The rise of AL_{ia} is caused by the higher $T_{h,set}$, resulting in a higher operative temperature in the beginning of the day. Although $T_{c,set}$ is lower, with T_{ia} controlled, the TABS are not able to reduce the temperature rise which occurs during the course of the day. Therefore, the maximum T_{op} will be higher. The top figure of Figure 5 illustrates this behaviour for typical days in each season. The bottom figure indicates that, for the same days, with the $T_{TABS,surf}$ setting, the adaptation of the $T_{h,set}$ and $T_{c,set}$ is capable of lowering the operative room temperature, and therefore increasing comfort.

The *EUI* increases for all controlled temperatures due to the increase in switching between heating and cooling (Table 10). The change for the different $T_{h,set}$ – $T_{c,set}$ settings is less pronounced for the TABS temperatures than for the air and operative temperatures.

Table 10: $ratio_{zone}$ for the different controlled temperatures as a function of $T_{h,set}$ - $T_{c,set}$

Ratio	**$T_{comfort,min}$ - $T_{comfort,max}$**	**($T_{comfort,min}$ + 1)-($T_{comfort,max}$ – 1)**	**($T_{comfort,min}$ + 1.25)-($T_{comfort,max}$ - 1.25)**
$Ratio_{zone,Tia}$	0.30	0.57	0.60
$Ratio_{zone,Top}$	0.20	0.50	0.57
$Ratio_{zone,TABS,core}$	0.13	0.19	0.26
$Ratio_{zone,TABS,surf}$	0.13	0.19	0.23

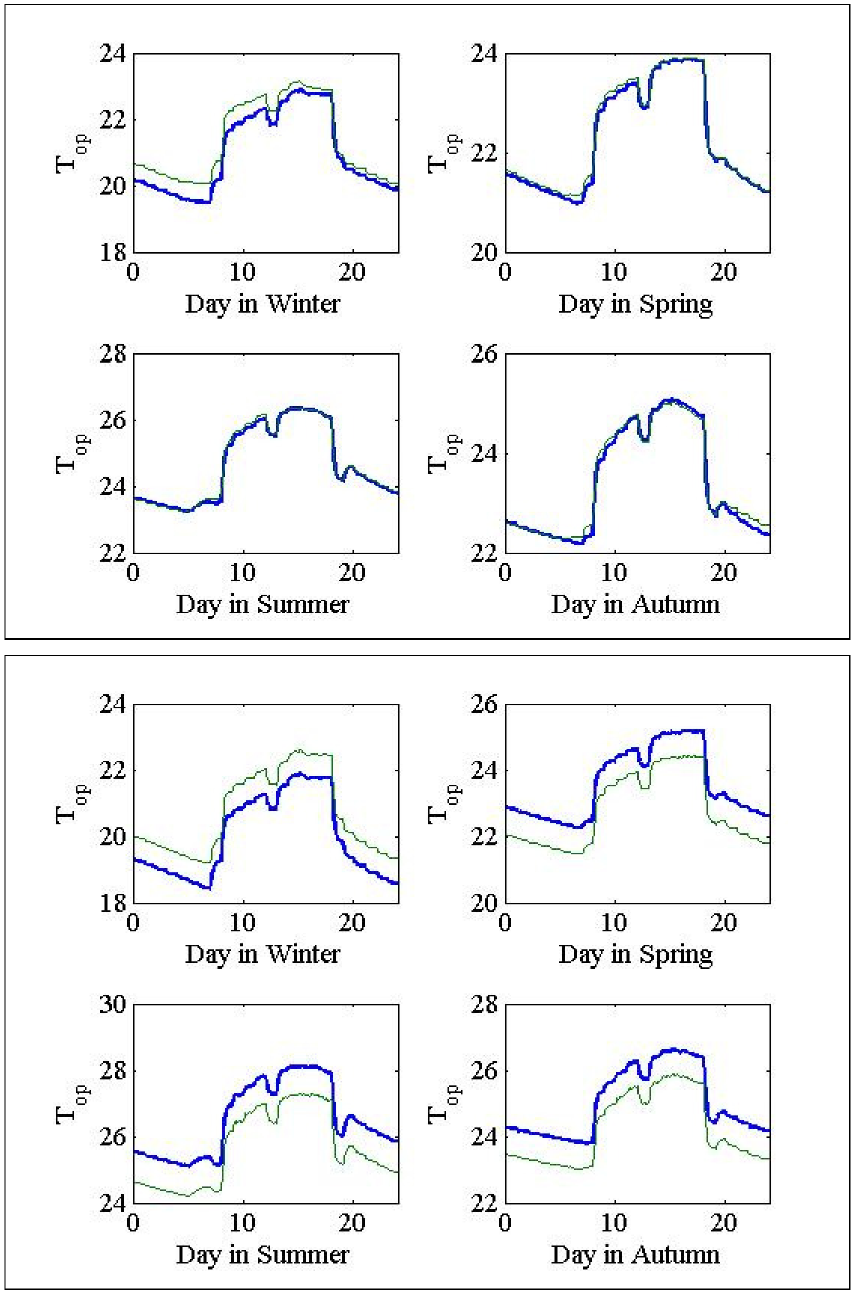

Figure 5: T_{op} for typical days of each season with T_{ia} (top figure) and $T_{TABS,surf}$ (bottom figure) as controlled temperature
(thick line: $T_{h,set}$ - $T_{c,set}$ = $T_{comfort,min}$ - $T_{comfort,max}$;
thin line: $T_{h,set}$ - $T_{c,set}$ = ($T_{comfort,min}$ + 1)-($T_{comfort,max}$ – 1))

4.5 TABS Case 4: Only changing cooling set points

Since the results from Section 4.2 show hardly any hours with an operative zone temperature T_{op} below the comfort limits, it is expected that only the upper limit $T_{comfort,max}$ should be lowered for the $T_{TABS,surf}$ and $T_{TABS,core}$ controller settings. Moreover, Section 4.4 demonstrates that raising $T_{h,set}$ causes an increased discomfort. This section shows the results for $T_{c,set}$ lowered with 1°C, resp. 2°C compared to $T_{comfort,max}$, while $T_{h,set}$ remains equal to $T_{comfort,min}$. The controller settings are presented in Table 11.

Table 11: Controller setting for TABS Case 4

	Controller settings
$T_{controlled}$	T_{ia}, T_{op}, $T_{TABS,core}$, $T_{TABS,surf}$
$T_{h,s} - T_{c,s}$	25-21
$T_{h,set}$- $T_{c,set}$	$T_{comfort,min}$- $T_{comfort,max}$; ($T_{comfort,min}$)-($T_{comfort,max}$ - 1); ($T_{comfort,min}$)-($T_{comfort,max}$ - 2)
Night setback	Yes
$T_{vent,s}$	22°C between 7 AM and 8 AM

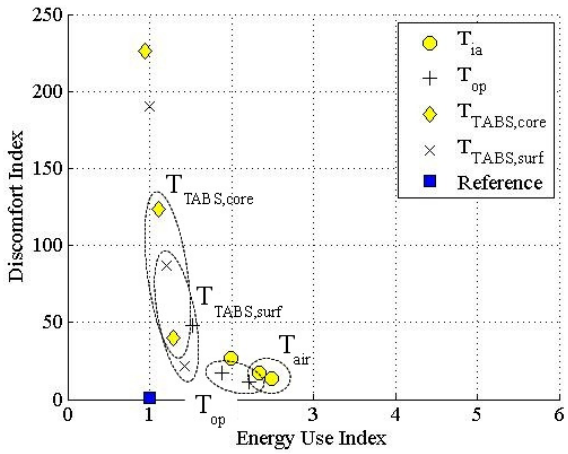

Figure 6: Influence of cooling set point $T_{c,set}$ (the adjusted settings are encircled)

These controller settings result in a major improvement compared to the settings of Section 4.4 with the *DI* of $T_{TABS,core}$ and $T_{TABS,surf}$ decreasing even further. Even the *EUI* for these two controlled temperatures (as well as the control based on T_{op}) decreases slightly (or even significantly for the T_{op} control) compared to Case 3 with adjusted heating and cooling set points (Figure 6 versus Figure 4). The T_{ia} setting shows a lower *DI* for the adapted settings compared to the '$T_{comfort,min}$- $T_{comfort,max}$' setting, contrary to the results of TABS Case 3.

The EUI remains higher for the adapted settings compared to the '$T_{comfort,min}$- $T_{comfort,max}$' setting. A remarkable observation can be made for the different controlled temperatures (Table 12). While the increase of Q_h is larger than the increase of Q_c for T_{ia} and T_{op}, this is no longer the case for $T_{TABS,surf}$ and $T_{TABS,core}$. The $ratio_{zone}$ also decreases for these two controlled temperatures with the adaptation of $T_{h,set}$- $T_{c,set}$. This means that the increase of the *EUI* for $T_{TABS,surf}$ or $T_{TABS,core}$ is not caused by a higher switching behaviour between heating and cooling, but merely by an increase of the cooling demand. This is in contrast to the previous cases where an EUI increase was always accompanied by an increase of $ratio_{zone}$. It can be concluded that adapting $T_{h,set}$- $T_{c,set}$ as done in 'TABS Case 4' leads to a lower switching behaviour for $T_{TABS,surf}$ or $T_{TABS,core}$ as the controlled temperature

Table 12 : Energy use (Q_h+Q_c) and discomfort (BL+AL) for the TABS Case 4 controller settings in absolute values (upper part) and relative to the '$T_{comfort,min}$- $T_{comfort,max}$' setting (lower part)

$T_{controlled}$	$T_{comfort,min}$- $T_{comfort,max}$		($T_{comfort,min}$)-($T_{comfort,max}$-1)		($T_{comfort,min}$)-($T_{comfort,max}$-2)	
	Q_h (kWh/m²)	Q_c (kWh/m²)	Q_h (kWh/m²)	Q_c (kWh/m²)	Q_h (kWh/m²)	Q_c (kWh/m²)
T_{ia}	12.84	42.93	17.03 (+33%)	48.28 (+12%)	19.11 (+48%)	50.79 (+18%)
T_{op}	6.98	35.53	10.61 (+52%)	42.08 (+18%)	14.72 (+111%)	47.11 (+33%)
$T_{TABS,core}$	3.02	23.60	3.11 (+3%)	28.01 (+19%)	3.4 (+12%)	32.60 (+38%)
$T_{TABS,surf}$	3.21	24.75	3.35 (+4%)	30.55 (+23%)	3.76 (+17%)	36.30 (+49%)
	Q_h+Q_c	BL+AL	Q_h+Q_c	BL+AL	Q_h+Q_c	BL+AL
T_{ia}	1	1	1.17	0.66	1.25	0.51
T_{op}	1	1	1.24	0.37	1.45	0.24
$T_{TABS,core}$	1	1	1.17	0.54	1.35	0.18
$T_{TABS,surf}$	1	1	1.21	0.46	1.43	0.11

Furthermore, Table 12 shows that for the T_{ia} setting, the increase in energy use (Q_h+Q_c) is the smallest, while the $T_{TABS,surf}$ setting takes the most advantage of lowering the $T_{c,set}$ control parameter with respect to the thermal comfort (BL+AL).

4.6 Summary of the controller settings analysis

Presenting all used controller settings (Table 13) on one figure results in Figure 7. Two points can be highlighted in these results. The first point (A) is the closest to the ideal system results and the second point (B) obtains a high comfort against a reasonable increase in energy use. Table 14 provides the data for these two points.

For all controlled temperatures, high heating supply temperatures and low cooling supply temperatures do not have a relevant effect on the energy performance and the thermal discomfort (Section 4.2). This conclusion is beneficial for coupling with a heat pump/direct cooling system, working at high efficiency for relatively high temperatures in cooling mode and low temperatures in heating mode. Where the results for $T_{TABS,core}$ or $T_{TABS, surf}$ are hardly influenced by the supply temperatures, controlling T_{ia} or T_{op} benefits from lower heating and higher cooling supply temperatures. This is caused by the decreased switching behaviour between heating and cooling for these controller settings.

Night setback (Section 4.3) has an influence on the energy performance for T_{ia} and to a smaller extent for T_{op}, but hardly none for $T_{TABS,core}$ and $T_{TABS, surf}$. Low operative zone temperatures in the first hours of occupation for a typical winter or midseason situation are preferably tackled by controlling the supply air temperature of the faster reacting AHU.

The cooling set point appears to be the key parameter in achieving a balance between thermal comfort and energy use in this office building characterized by a high cooling load. Lowering this set point allows the controller to take the TABS thermal inertia into account and to anticipate on the occurring heat gains.

Table 13: Controller settings for the summary figure (see Figure 7)

	Controller settings
$T_{controlled}$	T_{ia}, T_{op}, $T_{TABS,core}$, $T_{TABS,surf}$
$T_{h,s} – T_{c,s}$	25-21; 28-18
$T_{h,set}$- $T_{c,set}$	$T_{comfort,min}$- $T_{comfort,max}$; ($T_{comfort,min}$ + 1)-($T_{comfort,max}$ - 1); ($T_{comfort,min}$ + 1.25)-($T_{comfort,max}$ - 1.25); ($T_{comfort,min}$)-($T_{comfort,max}$ - 1); ($T_{comfort,min}$)-($T_{comfort,max}$ - 2)
Night setback	Yes
$T_{vent,s}$	22°C between 7 AM and 8 AM

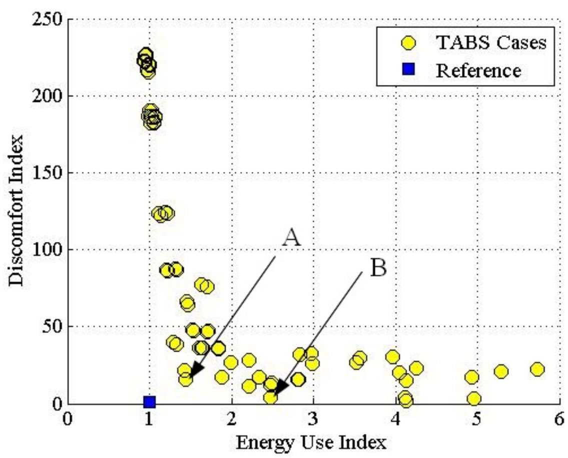

Figure 7: Energy Use Index against Discomfort Index for all the investigated controller settings as listed in Table 13

Table 14: Advisable controller settings

Controller setting	$\mathbf{T_{controlled}}$	$\mathbf{T_{h,s} – T_{c,s}}$	$\mathbf{T_{h,set}}$- $\mathbf{T_{c,set}}$	**EUI**	**DI**
A	$T_{TABS,surf}$	28-18	($T_{comfort,min}$)-($T_{comfort,max}$ - 2)	1.45	15.7
B	T_{op}	28-18	($T_{comfort,min}$)-($T_{comfort,max}$ - 1)	2.48	3.89

5. CONCLUSION

In this paper the influence of controller settings on the energy performance and thermal comfort of a TABS system in an office building is analysed for four controlled temperatures (indoor air temperature T_{ia}; operative temperature T_{op}; TABS surface temperature $T_{TABS,surf}$ and TABS core temperature $T_{TABS,core}$), different water supply temperatures, different heating and cooling set points, incorporation of night setback and ventilation supply temperature control. The analysis is performed on an office zone of the ICT3 building, which is part of a high quality office building complex in Leuven (Belgium).

The variation in energy performance and thermal comfort for changing controller settings is determined by the location of the controlled temperature sensor, with T_{ia} and T_{op} on the one hand sensing a temperature close to the operative room temperature and $T_{TABS,core}$ on the other hand being closer to the controlled water supply temperature. $T_{TABS,surf}$, lying in between these two positions, appears to be the optimal controlled temperature.

An optimal combination of controller settings depends on the assessment of the trade-off between energy use and thermal discomfort. Controller setting adjustment increasing the one performance indicator will decrease the other and vice versa. The simulations show that the combination of controlling $T_{TABS,surf}$ with a heating supply temperature of 28°C, a cooling supply temperature of 18°C, the heating set point equal to the lower thermal comfort limit and the cooling set point 2°C lower than the upper thermal comfort limit, in combination with night time setback and a ventilation supply temperature which controls the temperature drop during the beginning of the day, proves to represent the optimal controller settings for this office building. They are therefore recommended to use during the commissioning of the building. If $T_{TABS,surf}$ would turn out to be too difficult to use, due to the sensitivity of this controlled temperature to the location of the sensor, T_{op} proves to be a valuable alternative.

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